CF3. Dark Matter: Cosmic Probes

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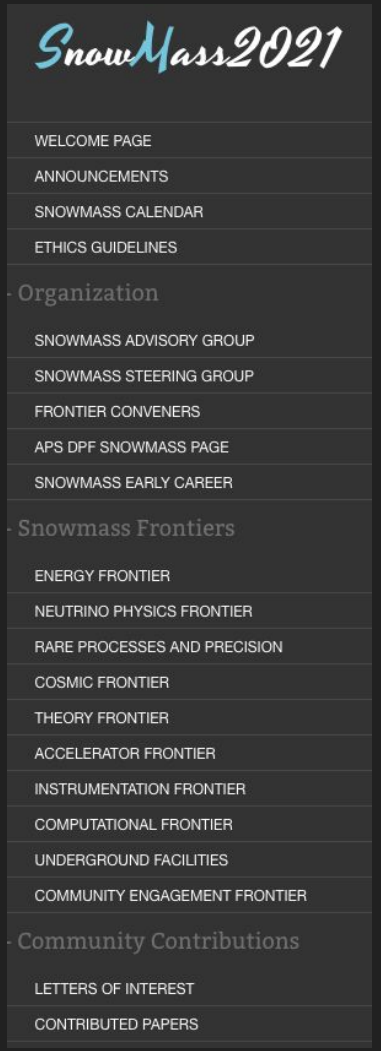
Agenda for this Meeting

- Introduction to Snowmass
  - Snowmass Timeline
- What is the Cosmic Frontier
- Dark Matter in Cosmic Frontier
- CF3. Dark Matter: Cosmic Probes
  - Is my science in CF1/CF2 or CF3? Maybe both.
- Examples of CF3 scope
  - Experiment/Hardware
  - Observations/Probes
  - Computation/Simulation
  - Theory/Models
- Snowmass Resources



What is Snowmass? (Borrowed from CF1)

- **Goal:** Organized by the Division of Particles and Fields (DPF) of the American Physical Society (APS), Snowmass is intended to define the most important questions for the particle physics community and to identify the most promising ways to address these questions in a global context. Snowmass provides an opportunity for the entire HEP community to come together to identify and document a vision for the future of particle physics in the US and its international partners.
  - Snowmass Virtual Town Hall presentations/recordings: https://indico.fnal.gov/event/23601/
  - Indico master site for Snowmass-related meetings: https://indico.fnal.gov/category/1098/
- **Organization:** Snowmass 21 > Cosmic Frontier (CF) > Topical Group CF3 = Dark Matter: Cosmic Probes
  - Get Connected to CF3
    - Fill out the interest form: https://forms.gle/iVnHVoGmgqUiZ2Jg7
    - Join the Slack channel (CF3): https://snowmass2021.slack.com/archives/C0129Q0E0RL
    - Join the email list (CF3): SNOWMASS-CF-03-DM-COSMIC@FNAL.GOV

Snowmass Timeline (Updated from CF1)

- **TODAY**: fill in this interest form: https://forms.gle/iVnHVoGmgqUiZ2Jg7
- **Aug 31, 2020**: Deadline for letters of interest (https://snowmass21.org/loi)
- ~~**Nov 4, 2020**: Snowmass planning meeting (Fermilab)~~
- **Oct 5, 2020**: Snowmass planning meeting (Virtual)
- **July 11, 2021**: Snowmass Summer Study (Seattle)
- **July 31, 2021**: Deadline for contributed papers (https://snowmass21.org/submissions)
- **End of 2021**: Final Snowmass report

- **Letters of Interest** (**Aug, 31, 2020**) (templates)
  - Up to 2 pages of “content” (not including author list & bibliography)
  - Should give brief descriptions of the proposal and cite the relevant papers
  - Inputs to Snowmass Planning Meeting (November 2020), allow conveners to see what proposals are coming and to encourage the community to begin studying them

What is the Cosmic Frontier?

- Snowmass 2021 structure maps (roughly) to the structure of DOE HEP.
- Current DOE statement about CF: “Cosmic Frontier researchers seek to understand the nature of the overwhelming majority of the contents of the universe by searching for evidence of mysterious dark matter and dark energy.”
- Snowmass 2021 Cosmic Frontier topics cover: dark matter, dark energy, and cosmic probes of other fundamental physics (e.g. neutrinos, inflation).
- There is a separate **Theory Frontier,** and we encourage theorists to engage with them as well.
- There is a separate **Instrumentation Frontier,** and we encourage experimentalists to engage with them as well.

Snowmass Dark Matter Context

- Snowmass 2013: Cosmic Frontier Dark Matter
  - CF1: WIMP Dark Matter Direct Detection (https://arxiv.org/abs/1310.8327)
  - CF2: Indirect Dark Matter Detection (https://arxiv.org/abs/1310.7040)
  - CF3: Non-WIMP Dark Matter (https://arxiv.org/abs/1310.8642)
  - CF4: Dark Matter Complementarity (https://arxiv.org/abs/1305.1605)
  - Cosmic Frontier Report (https://arxiv.org/abs/1401.6085)
  - Snowmass was used as input for generating the P5 Report

- Snowmass 2021: Cosmic Frontier Dark Matter
  - CF1: Dark Matter: Particle-like
  - CF2: Dark Matter: Wave-like
  - CF3: Dark Matter: Cosmic Probes
  - [CF7: Cosmic Probes of Fundamental Physics]

Snowmass 2013 : Dark Matter Context

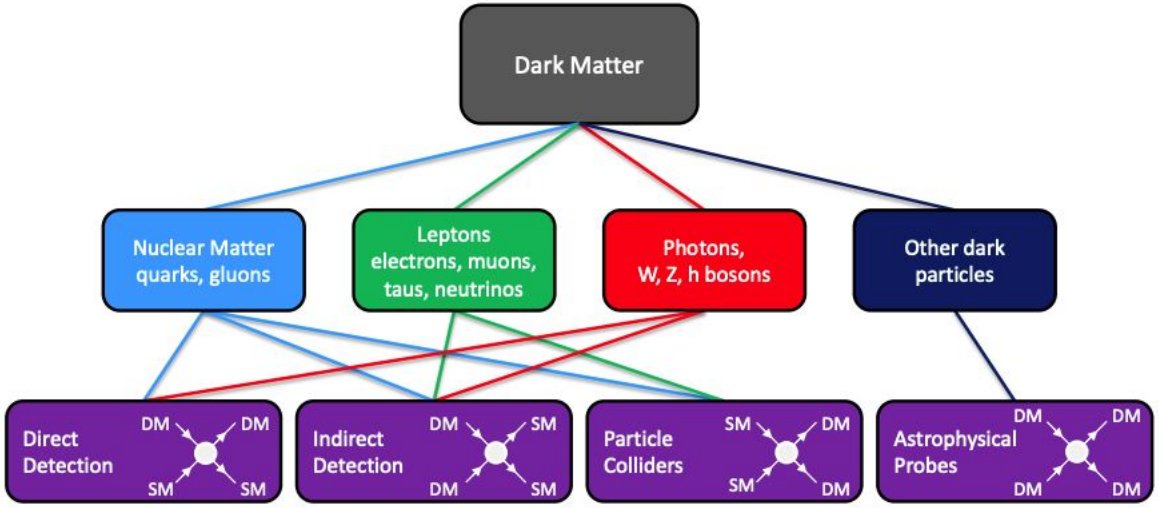


Figure 4-9. *Dark matter may have non-gravitational interactions with one or more of four categories of particles: nuclear matter, leptons, photons and other bosons, and other dark particles. These interactions may then be probed by four complementary approaches: direct detection, indirect detection, particle colliders, and astrophysical probes. The lines connect the experimental approaches with the categories of particles that they most stringently probe. The diagrams give example reactions of dark matter (DM) with Standard Model particles (SM) for each experimental approach. From Ref. [130].*

https://arxiv.org/abs/1305.1605; https://arxiv.org/abs/1401.6085

2014 P5 without CF3...

The last P5 report did not identify dark matter as a science driver for several large CF experimental efforts (LSST, DESI, CMB-S4).

DOE is now resistive to expanding the scientific scope of these experiments to support dark matter research *even though* dark matter is a DOE mission priority.

We would like to avoid having this happen again...

https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf

Table 1
Summary of Scenarios

	Scenarios			Science Drivers					
Project/Activity	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓	X	✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓	X	✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓	X	✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

What is CF3. Dark Matter: Cosmic Probes?

“This group covers uniquely astrophysical probes of dark matter, including via its impact on the structure and dynamics of galaxies, and through its interactions with astrophysical objects. This is a broad range of astrophysical/cosmological probes.”

- Dark matter properties that can *only* be probed by gravity are the sole domain of CF3; however, the dark matter landscape is complex…
- Is it easier to think about what CF3 *is not*?
  - CF1 Dark Matter: Particle-like: covers direct and indirect detection searches for massive particles (mass $\gtrsim$ 1 eV).
  - CF2 Dark Matter: Wave-like: covers low-mass dark matter direct detection and direct products.
- **Expansive definition of CF3 by exclusion:** “If the dark matter or its direct products hit detectors on/around Earth, it is CF1/CF2. Otherwise, it is CF3.”
- **When in doubt, submit to multiple groups!**

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CF1

Direct detection experiments; indirect detection of annihilation/decay (gamma-rays, X-rays); ...

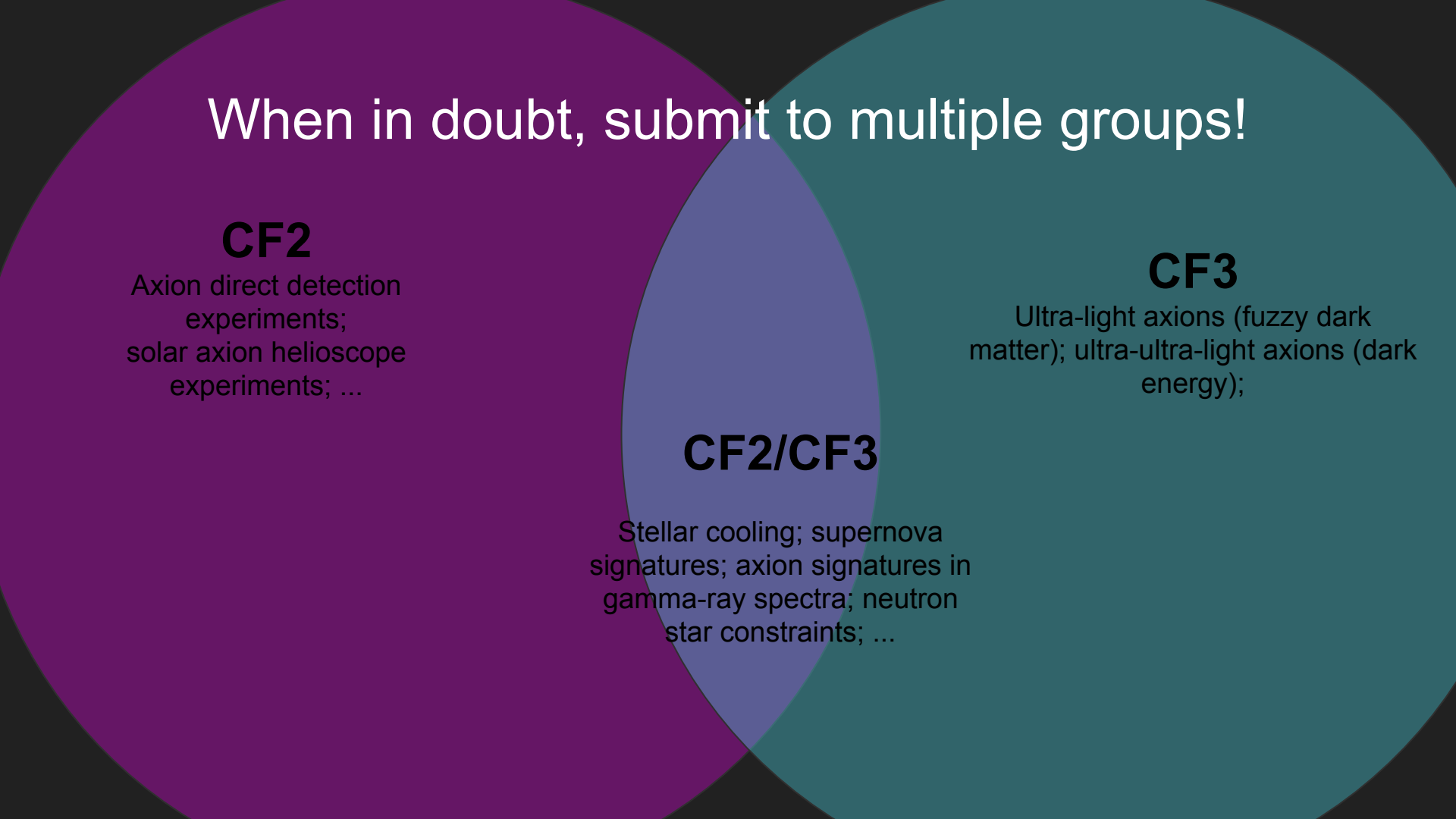
CF1/CF3

Cosmological constraints on dark matter--baryon interactions; CMB constraints on dark matter decay/annihilation; astrophysical input into direct/indirect detection (J-factors & local DM density)...

CF3

Gravitational probes of dark matter; dark matter self-interactions; macroscopic dark matter (PBHs); ...

When in doubt, submit to multiple groups!



Example: Experimental Efforts

- Large experimental efforts benefit from broad science programs that are aligned with DOE mission priorities. Dark matter is one such driver.
- Below are examples of experimental efforts (at least partially) targeting dark matter. These are efforts **that we are aware of**; one major goal is to expand this list
  - **Current generation:**
    Rubin Observatory/LSST, CMB-S4, DESI, DES, SPT, ACT
  - **Next generation:**
    Maunakea Spectroscopic Explorer (MSE), MegaMapper, CMB-HD, 30-m telescopes(GMT, TMT?), 21cm intensity mapping, neutrino experiments, …
  - **Instrumentation:**
    Low-noise detectors for optical and CMB instruments, optical fiber positioners, radio telescopes(?). What is unique instrumentation is needed for dark matter science?

Example: Observational Probes

Again, a major goal of the LOIs is to increase the sample of observational probes.

- Small-scale structure (dwarf galaxies, strong lensing, stellar streams)
- Anomalous stellar cooling (axions, dark photons)
- CMB probes of light degrees of freedom
- Self-interacting dark matter (colliding clusters, dwarf galaxies, galaxy rotation curves)
- Microlensing of primordial black holes

Examples at the boundary:

- CMB distortions from dark matter annihilation or decay (CF1?)
- Solar axions (physics is the same as stellar populations) (CF2?)
- LIGO measurements of black holes (CF7?)

Example: Simulation & Computation

- How do we disentangle dark matter physics from baryon physics?
- What simulation and modelling efforts are needed to make progress in this direction?
  - N-body simulations of alternative dark matter models have been very powerful tools, but are often computationally expensive. Can we develop analytical methods that observers and theorists could use?
- As sensitivity and data volume increases what new algorithms are required to extract dark matter science (also look at the Computation Frontier)?
  - Machine learning and artificial intelligence are now a common element in the analysis of cosmological data. What computational tooling is necessary for dark matter?
- How do we better integrate observation, analysis, simulation, theory, and modeling in the coming decade?

Example: Theory & Modelling

- How do we better characterize dark matter models/theories according to cosmic/astro observables?
- Existing examples:
  Number of light species (N_eff), free-streaming length, fuzzy dark matter, self-interaction cross sections...
- Given increasing experimental sensitivity and novel dark matter theories, do we need to introduce new variables?
- More generally, how to interpret cosmic/astro results in a way that particle physicists could understand and implement in their own work
- It is critical to break the “language” barriers among different subfields

We hope to achieve the following goals

- Explore dark matter science cases for experiments coming in the near-term (e.g., Rubin Obs., DESI, CMB-S4) and longer term (e.g., MSE, MegaMapper, CMB-HD)
- Identify areas of modelling and simulation efforts
- Define/examine benchmark cases to motivate cosmic probes of fundamental dark matter physics.
- Break the “language” barrier between different areas of expertise (experimentalists, observers, theorists and simulators) and between subfields of dark matter research (both within the Cosmic Frontier and across HEP)
- Demonstrate to the community and funding agencies that “cosmic probes” are one of the most promising way to unveil the nature of dark matter.

Getting Involved, Staying in Touch

- Please fill out the the form to help us gauge community interests: https://forms.gle/iVnHVoGmgqUiZ2Jq7
- We plan to hold a community meeting once a month to provide updates.
- We strongly encourage people to join the Snowmass2021 Slack. Information about how on the Snowmass website.
  - Channels to join: #cf03-dark_matter_cosmic and #dark_matter.
- Or to the conveners directly: kadrlica@fnal.gov, chanda.prescod-weinstein@unh.edu, hai-bo.yu@ucr.edu
- Questions? Don’t hesitate to reach out.

Resources available

- Snowmass2021 Wiki: https://snowmass21.org/cosmic/start
- Letter of Intent Template (due Aug 31): https://snowmass21.org/cosmic/start#submissions
- Snowmass 2013 Cosmic Frontier working group summary: https://arxiv.org/abs/1401.6085
- Snowmass 2013 Cosmic Frontier topic and contributed papers: https://www.slac.stanford.edu/econf/C1307292/docs/CosmicFrontier.html
- CF1. Particle Dark Matter kick-off slides: https://indico.fnal.gov/event/43903/attachments/130436/158935/CF1._Dark_Matter_Particle-Like_Kick-off_Meeting.pdf

Kickoff Discussion:

- Comments?
- Questions?
- Concerns?